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Sensitivity Quantification of Jointed Plain Concrete Pavement Mechanistic-Empirical Performance Predictions

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Abstract:

This paper focuses on quantitative and qualitative sensitivity analyses of various jointed plain concrete pavement (JPCP) mechanistic-empirical design scenarios. Two base cases of JPCP types were utilized: (1) new construction on granular base (new JPCP case), and (2) both new construction/reconstruction on stabilized foundations or rehabilitation on underlying asphalt/concrete layers (JPCP over stiff foundation case). Each base case was designed for three traffic levels in five climate zones to evaluate the sensitivity of predicted distresses using the American Association of State Highway and Transportation Officials (AASHTO) mechanistic-empirical pavement design guide (MEPDG) procedure. Sensitivity is characterized by a design limit normalized sensitivity index (*NSI*), which can be interpreted as the percentage change in predicted distress relative to the design limit caused by a given percentage change in the design input. For JPCP types and distresses, the sensitivities of the design inputs for the Portland cement concrete (PCC) surface layer were the most important. The findings suggests that more caution is required to select PCC slab design features and PCC material properties in JPCP design using MEPDG and DARWin-ME™ for designing cost-effective and sustainable concrete pavements.

Keywords: Concrete; Pavement; Sensitivity Analyses; Design; AASHTO

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1. Introduction

The latest American Association of State Highway and Transportation Officials (AASHTO) pavement design software, DARWin-ME™, is a significantly improved methodology for the analysis and design of pavement structures. It builds upon the latest version (version 1.1) of national cooperative highway research program (NCHRP) mechanistic-empirical pavement design guide (MEPDG) for providing pavement analysis and performance predictions under various "what-if" scenarios.

The mechanistic part of MEPDG is the application of the engineering mechanics principles to calculate pavement responses (stresses, strains, and deflection) under loads. Thermal and moisture distributions are also mechanistically determined using an enhanced integrated climate model (EICM). The empirical nature of the MEPDG is the use of calibrated or adjusted relationships between mechanistic pavement responses and the field measured distresses for predicting pavement performance history. Note that MEPDG performance predictions for jointed plain concrete pavement (JPCP) are faulting, transverse cracking, and international roughness index (IRI). As the official AASHTOW are Pavement ME Design software, DARWin-ME™ employs the latest version of research grade MEPDG software (version 1.1) in pavement analysis and performance predictions. Additional key features and enhancements in DARWin-ME™ over the MEPDG include utilization of more hourly climate data for future climate condition predictions, tool to optimize for thickness design, tool to import backcalculation results for rehabilitation designs, etc.

The performance predictions as end results of MEPDG and DARWin-ME™ can help State highway agencies to assess maintenance and rehabilitation needs over the life of the pavement structure. MEPDG and DARWin-ME™ have significant potential to upgrade the efficiency of pavement analysis and designs. However, it requires a significant understanding of numerous pavement design input properties that characterize the pavement materials, layers, design features, and conditions. MEPDG sensitivity studies for rigid pavements began appearing in the literature immediately after the initial release of the MEPDG in 2004 to derive a better understanding of how the required design input values affect performance predictions [1-21].

The procedures and findings of all previous studies related to both rigid and flexible pavements are summarized by Schwartz et al [29]. Common findings derived from previous studies which are also relevant to the present study include: (1) consistent trends of JPCP performance predictions with prevailing pavement engineering knowledge, (2) reasonable sensitivities to traffic level, climate zone, and PCC thickness, and (3) PCC coefficient of thermal expansion (CTE) is one of the most sensitive inputs influencing JPCP performance predictions. Some concerns related to past studies include: (1) varying only a small subset of inputs in local conditions, (2) sensitivity analysis approaches without quantitative interpretation – e.g., not answering that "if input x goes up by n%, output y goes down by m%.", and (3) not using MEPDG version 1.1 which forms the main framework of DARWin-ME™." To resolve these concerns, the NCHRP 1-47 project, "Sensitivity Evaluation of MEPDG Performance Prediction", was initiated and recently completed [29].

This paper (a subset of the NCHRP 1-47 project) focuses on comprehensive sensitivity analyses of various JPCP design scenarios. JPCP designs representing new construction and rehabilitation conditions at three traffic levels in five climate zones were chosen for evaluating the sensitivity of distresses predictions using MEPDG (version 1.1). One-at-a-time (OAT) sensitivity analysis (SA) was implemented using a design limit normalized sensitivity index

(NSI) to provide both quantitative and qualitative sensitivity information. The procedure and the results of sensitivity analyses are discussed in this paper highlighting the significant design input properties required for conducting routine MEPDG and DARWin-ME™ rigid pavement analysis and design.

2. Sensitivity Analysis

SA is the apportionment of output variability from a model to its various inputs. SA draws upon many of the same concepts as the design of experiments. The design of experiments theory provides a framework for selecting the combinations of factor values that will provide the most information on the input-output relationships in the presence of variation [22, 23].

The classical approach is factorial design. For example, consider a model having k inputs. In order to evaluate the effect of each input on the model output, each input is varied over l levels—e.g., minimum, average, and maximum values for l=3. A full factorial experimental design then evaluates the model for all combinations of inputs and levels—i.e., l^k combinations. The full factorial experiment permits assessment of the main effect of each variable (i.e., the average effect of that variable over all conditions of other factors) as well as interactions. The principal disadvantage of full factorial experimental designs is that the l^k number of combinations quickly becomes very large as the number of inputs, k increases. Unfortunately, most models, including the MEPDG, have large sets of input parameters and are computationally expensive to evaluate. Reducing the number of combinations is the motivation for various partial or fractional factorial design techniques (e.g., blocking, aliasing, etc.).

Local SA provides an economical approach for identifying the subset of inputs that have the largest impact on the outputs. Only the sensitivities around the reference input values for the baseline cases are evaluated—i.e., the evaluation is only for very small regions of the overall solution space. This provides only a "local" as opposed to a "global" sensitivity evaluation. The drawback of most standard local SA is that it tends to provide only qualitative sensitivity information—e.g., a ranking of input parameters in terms of their importance. However, these methods can be used to reduce the search space for subsequent quantitative sensitivity analysis.

OAT methods are the most common type of local SA. In standard OAT applications, one or more baseline scenarios are exercised by varying each input independently. The number of model evaluations required by OAT techniques is on the order of k (rather than the l^k combinations required for a full factorial experimental design).

To overcome the main drawback of most standard local SA providing only qualitative sensitivity information (a ranking of input), this study implemented OAT SA using a design limit *NSI* to provide both quantitative and qualitative sensitivity information. Note that quantitative sensitivity information here is the physical interpretation of sensitive analysis results. The *NSI* used in this study is "design limit" normalized sensitivity index S_{jk}^{DL}:

$$NSI = S_{jk}^{DL} = \frac{\Delta Y_j}{\Delta X_k}\frac{X_k}{DL_j} \quad (1)$$

in which X_k is the baseline value of design input k, ΔX_k is the change in design input k about the baseline, ΔY_j is the change in predicted distress j corresponding to ΔX_k, and DL_j is the design limit for distress j.

The *NSI* always uses the design limit as the normalizing factor for the predicted distress. *NSI* can be interpreted as the percentage change in predicted distress relative to the design limit caused by a given percentage change in the design input.

For example, consider faulting of JPCP as the predicted distress with a design limit of 3.05 mm (0.12 inches). An *NSI* of -0.19 for the sensitivity of faulting to 28-day Portland cement concrete (PCC) modulus of rupture (*MOR*) implies that a 10% increases in 28-day PCC *MOR* will decrease faulting by $\Delta X_k \times NSI$ =1.9% of its design limit DL_j--i.e., it will decrease faulting by 0.10 (ΔX_k) × 0.19 (*NSI*) × 3.05 (design limit for JPCP faulting) = 0.058mm (0.00228 inches).

3. Sensitivity Analysis Inputs

Sensitivity analyses were conducted for the full ranges of all model inputs and outputs. However, not all combinations of model input values are physically plausible. For example, a thick rigid pavement on stiff foundation subjected to low traffic volume does not represent a realistic scenario likely to be encountered in practice. Therefore, a set of base cases were made to cover the ranges of commonly encountered pavement types, climate conditions and traffic levels.

The JPCP types considered are a 'new JPCP' and a 'JPCP over stiff foundation'. New JPCP represents new construction on granular base foundation. JPCP over stiff foundation intends to represent both new construction/reconstruction on stabilized foundations or rehabilitation on underlying asphalt/concrete layers. Each JPCP type was designed for three traffic levels in each of five climatic zones as base cases. Thus, the total number of base cases evaluated in this sensitivity analyses are 30 (2 pavement types x 5 climates x 3 traffic levels).

3.1. Global inputs for JPCPs

There are two sets of global inputs used in all OAT analyses: climate conditions and traffic levels. Five climate zones utilized for base case are hot-dry, hot-wet, temperate, cold-dry and cold-wet. Table 1 summarizes the specific locations and the weather station used to generate the climate files for each of the five climate zones.

The three traffic levels used in all OAT analyses are summarized in Table 2. The baselines of average annual daily truck traffic (AADTT) values are designed to fall within the low (<5,000), medium (5,000-10,000), and high (>15,000) truck volume categories in the FHWA *FAF Freight Traffic Analysis Report* [24]. To put these traffic volumes into a more familiar context, the approximate numbers of equivalent single axle loads (ESALs) are also included in Table 2. The AADTT ranges for varying AADTT values in each of traffic categories are listed in Table 2.

Table 1. Climate categories for base cases.

Climate Category	Location	Weather Station	Mean annual air temperature (ºC)	Min temperature (ºC)	Max temperature (ºC)	Mean annual rainfall (mm)
Hot-Wet	Orlando, FL	ORLANDO INTERNATIONAL ARPT	22.0	11.3	31.8	1,271
Hot-Dry	Phoenix, AZ	PHOENIX SKY HARBOR INTL AP	23.9	11.9	35.7	171
Cold-Wet	Portland, ME	PORTLAND INTL JETPORT ARPT	8.3	-4.7	22.1	999
Cold-Dry	International Falls, MN	FALLS INTERNATIONAL ARPT	4.2	-13.0	19.7	642
Temperate	Los Angeles, CA	LOS ANGELES INTL AIRPORT	10.1	10.1	26.9	360

Table 2. Traffic ranges for base cases.

Traffic Category	Baseline Inputs		AADTT Range
	AADTT[1]	Est. ESALs[2]	
Low	1,000	5M	500-5,000
Medium	7,500	25M	5,000-10,000
High	25,000	75M	20,000-30,000

[1]Based on MEPDG Interstate Highway TTC4 Level 3 default vehicle distribution.
[2]Based on 25 year design life.

3.2. Special input considerations for JPCPs

3.2.1. PCC stiffness and strength

The MEPDG needs PCC stiffness and strength design inputs at all three input levels as per the hierarchical input level classification employed by the MEPDG. Level 1 of the MEDPG requires direct measurements of the modulus of elasticity (E) and the *MOR*. The required stiffness and strength values at level 2 are estimated from unconfined compressive strength (f_c') results at various ages. At level 3, they are estimated from a single point measurement of the concrete modulus of rupture or compressive strength and optionally the corresponding modulus of elasticity at 28 days.

A previous study [25] reported that all three MEPDG PCC input levels provided comparable predictions for faulting and to a lesser extent for international roughness index (IRI), but different predictions for transverse slab cracking. The most important finding from this study suggested that the use of level 3 inputs of measured 28-day MOR and E is a suitable alternative to Level 1 for MPEDG rigid pavement predictions. Based on these results, level 3 inputs of measured 28-day MOR and E were utilized in this study.

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3.2.2. Unbound material properties

The MEPDG needs unbound material gradation and plasticity as inputs to estimate the soil water characteristic curve (SWCC) parameters (a_f, b_f, c_f, and h_r). These gradation and plasticity parameters are highly correlated to resilient modulus (M_r), which in turn is primarily a function of the soil type. Therefore, to have a consistent set of unbound material properties, design input values for the gradation and plasticity parameters should be adjusted when a design input value for M_r is varied.

Prior studies [26, 27] developed regression models for relating gradation and plasticity parameters to M_r. In these models, gradation data giving compatible values of the percent passing no. 200 sieve (P_{200}) and grain diameter at 60% passing (D_{60}) are determined from a design input value for M_r via correlations along with compatible values for plasticity index (PI) and liquid limit (LL). This approach was utilized in OAT analyses for evaluating unbound material property design inputs.

3.2.3. Edge support conditions

Categories for edge support in MEPDG JPCP analysis are: (1) no support, (2) tied PCC, and (3) widened slab. In the OAT analyses, these edge support conditions are equivalent to load transfer efficiency (LTE) or slab widths. The "no support condition" represented as a 5% LTE and 12-ft slab width was selected as the base condition. The distress predictions under the no support condition were compared to those for two other LTE values (50% and 80%) for the tied PCC option or for two slab widths (13ft and 14ft) for the widened slab option.

3.3. Analysis inputs

The OAT analyses of each JPCP type (new JPCP and JPCP over stiff foundation) encompassed a total of 15 base cases consisting of five climate zones and three traffic levels. Table 3 presents project-specific parameters that were fixed for all JPCP analyses. Table 4 summarizes the design inputs that are related to traffic levels. Higher traffic levels require correspondingly thicker PCC and base layers. The baseline value, reduced value ("low"), and increased value ("high") for the PCC and granular base layers are listed under each traffic level category.

Table 3. Fixed design inputs for all JPCP cases.

Input Parameter	**Value**
Design Life	25 years
AADTT Category	Principal Arterials – Interstate and Defense Route
Truck Traffic Classification (TTC)	4
Number of Lanes in Design Direction	2 for low traffic/ 3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic /55 for medium traffic /50 for high traffic
Default Growth Rate	No Growth
First Layer Material Type	Portland Cement Concrete
Second Layer Material Type	Granular base for new JPCP/ Stabilized base for JPCP over Stiff.
Subgrade Material Type	Soil

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Table 4. Design inputs related to traffic levels in all JPCP cases.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	**Low**	**High**	**Baseline**	**Low**	**High**	**Baseline**	**Low**	**High**
AADTT									
Nominal AADTT	1,000	500	5,000	7,500	5,000	10,000	25,000	20,000	30,000
Design Lane AADTT	375	188	1,875	2,063	1,375	2,750	6,250	5,000	7,500
New JPCP									
PCC Thick., mm	203	152	254	254	203	305	305	254	356
Base Thick., mm	102	51	152	152	76	229	203	127	305
JPCP over Stiff.									
PCC Thick., mm	203	178	229	229	203	254	279	229	330
Base Thick., mm	102	76	152	152	102	203	203	152	254

The remaining design inputs that were varied during the OAT sensitivity analyses are summarized in Table 5. The baseline value, reduced value ("low"), and increased value ("high") are listed for each design input. Absolute terms and multiplicative factors were also utilized to describe the decreases/increases from the baseline values.

4. Sensitivity Analysis Results

4.1. Base case performance predictions

Over 30 design inputs in Table 5 are varied for 15 base cases (5 climate zones and 3 traffic levels) of each JPCP type in the OAT sensitivity analyses. This required over 1,000 MEPDG runs for the JPCP scenarios. The predicted distresses at the 50% reliability level for the JPCP baseline scenarios are summarized in Table 6. The predictions span a wide range of magnitudes (including values beyond the design limits) for all distresses. When interpreting Table 6, it is important to keep in mind the objectives of the OAT sensitivity analyses: the precise magnitudes of the predicted distresses are not the focus but rather how these predicted distresses vary as each design input is varied about its baseline value.

A *NSI* value is calculated for each design input-pavement distress combination for each of the base cases. The *NSI* values for all distresses of both new JPCP and the JPCP over stiff foundation cases are summarized through Fig.1 to Fig. 6.

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Table 5. Input parameters and variations in all JPCP cases.

Input Parameter[1]	**Baseline Value**	**Low**	**High**
Construction Month	July 2006	March 2006	October 2006
Design Lane Width (DLW), ft.	12	11	N/R[2]
Joint Spacing, ft.	15	10	20
Dowel Diameter, in.	1.2	1.0	1.5
Edge Support – LTE, %	5 (no support)	N/R[2]	50, 80
Edge Support – Widened Slab, ft.	12 (no support)	N/R[2]	13, 14
Erodibility Index	3	1	5
Surface Shortwave Absorption (SSA)	0.85	0.80	0.98
PCC Unit Weight, pcf	150	140	160
PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coef. of Thermal Expansion (CTE). Per F° x 10^{-6}	5.56	2	10
PCC Thermal Conductivity, BTU/hr-ft-F°	1.25	0.5	2
Cement Content, lb/yd^3	500	400	700
Water/Cement Ratio (W/C)	0.4	0.3	0.7
PCC Modulus of Rupture at 28 days (28-day MOR), psi	620	496	744
PCC Elastic Modulus at 28 days (28-day E), psi	3,956,571	3,165,257	4,747,885
Base Liquid Limit (LL)[3,4], %	Varied	0.9 × Baseline	1.1 × Baseline
Base Plasticity Index (PI)[3,4], %	Varied	0.9 × Baseline	1.1 × Baseline
Base D60[3,4], mm	Varied	0.9 × Baseline	1.1 × Baseline
Base N200[3,4], %	Varied	0.9 × Baseline	1.1 × Baseline
Base Poisson's Ratio (PRatio)[4]	0.35	0.315	0.385
Base Ko[4]	0.5	0.45	0.55
Base Resilient Modulus (M_r)[4], psi	25,000	15,000	40,000
Stabilized Base Resilient Modulus (M_r)[5], psi	100,000	40,000	3,000,000
Subgrade Liquid Limit (LL)[3], %	Varied	0.9 × Baseline	1.1 × Baseline
Subgrade Plasticity Index (PI)[3]	Varied	0.9 × Baseline	1.1 × Baseline
Subgrade D60[3], mm	Varied	0.9 × Baseline	1.1 × Baseline
Subgrade N200[3], %	Varied	0.9 × Baseline	1.1 × Baseline
Subgrade Poisson's Ratio (PRatio)	0.35	0.315	0.385
Subgrade Ko	0.5	0.45	0.55
Subgrade Resilient Modulus(M_r), psi	15,000	10,000	20,000
Ground Water Depth (GWD), ft.	10	2	18
Loss of Full Friction[5], months	136	0	150

[1]All units are same as ones used in MEPDG software
[2]N/A is not required.
[3]Baseline value is estimated from correlation of resilient modulus and the ranges of variations are ±10% of baseline value
[4]Input parameters and variations only for new JPCP cases
[5]Input parameters and variations only for JPCP over stiff foundation cases

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Table 6. Predicted distress levels for JPCP baseline scenarios.

Type	**Traffic**	**Climate**	**PCC, mm**	**Base, mm**	**Faulting, mm**	**Trans. Crack, %**	**IRI, m/km**
New JPCP	Low	Hot-Wet	203	102	0.20	4.8	1.14
	Low	Hot-Dry	203	102	0.23	13.7	1.26
	Low	Cold-Wet	203	102	0.46	9.7	1.66
	Low	Cold-Dry	203	102	0.23	14.6	2.25
	Low	Temperate	203	102	0.13	1.5	1.07
	Medium	Hot-Wet	254	152	1.17	2.0	1.42
	Medium	Hot-Dry	254	152	1.32	7.2	1.53
	Medium	Cold-Wet	254	152	2.26	2.4	2.11
	Medium	Cold-Dry	254	152	1.14	5.0	2.38
	Medium	Temperate	254	152	0.81	0.4	1.28
	High	Hot-Wet	305	203	3.33	0.5	2.10
	High	Hot-Dry	305	203	3.96	2.1	2.32
	High	Cold-Wet	305	203	4.24	0.6	2.71
	High	Cold-Dry	305	203	2.72	1.5	2.83
	High	Temperate	305	203	2.59	0.1	1.85
JPCP over Stiff.	Low	Hot-Wet	203	102	0.13	7.3	1.15
	Low	Hot-Dry	203	102	0.13	22.7	1.35
	Low	Cold-Wet	203	102	0.30	21.9	1.77
	Low	Cold-Dry	203	102	0.15	30.9	2.44
	Low	Temperate	203	102	0.05	1.6	1.06
	Medium	Hot-Wet	229	152	0.76	7.6	1.36
	Medium	Hot-Dry	229	152	0.94	30.9	1.72
	Medium	Cold-Wet	229	152	1.68	21.6	2.19
	Medium	Cold-Dry	229	152	0.86	41.2	2.78
	Medium	Temperate	229	152	0.46	1.6	1.18
	High	Hot-Wet	279	203	1.78	1.0	1.60
	High	Hot-Dry	279	203	2.44	5.8	1.88
	High	Cold-Wet	279	203	3.05	1.1	2.34
	High	Cold-Dry	279	203	2.13	3.9	2.68
	High	Temperate	279	203	1.14	0.1	1.38
Design Limit					3.05	15.0	2.71

4.2. Faulting performance predictions

Fig. 1 present the *NSI* values for faulting of new JPCP. PCC unit weight, dowel diameter and edge support with widened slab rank as the three most sensitive design inputs with *NSI* values ranging from -0.2 to -3.4. These *NSI* values imply that a 10% increases in these inputs will decrease faulting by 2% to 34 % of its design limit of 3.05 mm (0.12 inches). The negative sign of the *NSI* values means that faulting decreases with increases in values of these design inputs. Note that the ranges of *NSI* values are related to variations of each design input among 15 base cases. The PCC unit weight is a critical factor in the calculation of critical responses in the rigid pavement structural response models employed in the MEPDG. An increase in unit weight can decrease curling deflections, which can reduce faulting. The increases in dowel diameter are highly effective for reducing faulting by increasing the transverse joint LTE. The use of a wider slab reduces deflections by keeping the vehicle axles well away from the free edge and corners. Note that vehicle loading on free edge and corners can cause large stresses and strains in the pavement slabs.

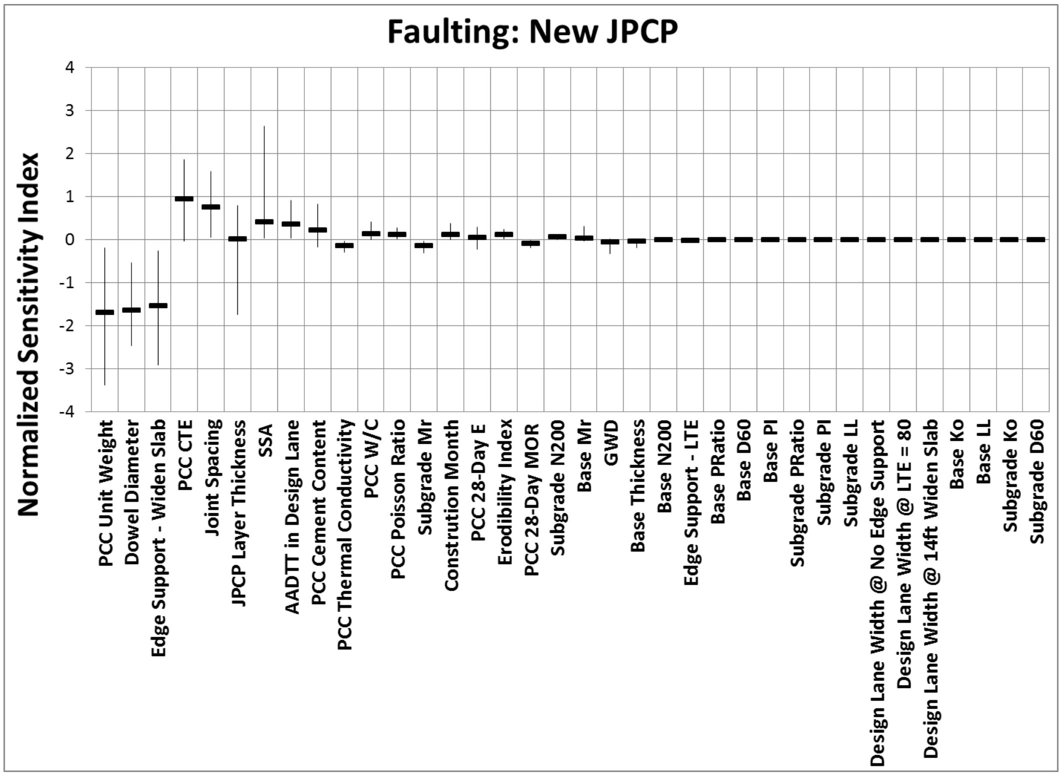

Fig. 1. NSI values for faulting in new JPCP.

The next three most sensitive design inputs are PCC coefficient of thermal expansion (CTE) with *NSI* values varying up to 1.9, joint spacing with *NSI* values varying up to 1.6, and the PCC slab thickness with *NSI* values ranging from -1.7 to 0.8 . The positive signs of the *NSI* values for these inputs mean that faulting increases with increases in values of these design inputs. A larger PCC CTE can cause higher curling deflections resulting in increased faulting. The decrease in predicted faulting with decreasing joint spacing could be explained by one that the shorter joint spacing results in smaller joint openings which can reduce chance of faulting distress [28]. Although it has been recognized that slab thickness affects slab cracking very significantly and faulting to a lesser extent, it was unexpected that faulting would increase as slab thickness increased in some cases in this analysis. This can be attributed to the reduction of dowel shear effectiveness.

An increase in PCC thickness leads to a decrease in the ratio of dowel cross-section to PCC cross-section [28]. Thus, an increase in PCC thickness may require a correlated increase in dowel diameter to avoid an increase in faulting. Note that the OAT analysis for PCC thickness varied only PCC thickness design inputs with fixed values of the other design inputs including dowel diameter.

Surface shortwave absorption (SSA), AADTT, cement content, and PCC thermal conductivity are the next most sensitive design inputs. Higher cement content and SSA may increase the drying shrinkage at the surface of the PCC slab, which may increase faulting due to increased warping deflection. Identification of AADTT as a sensitive input agrees with engineering experience. Higher thermal conductivity can decrease curling deflection by reducing temperature differences between the top and bottom of PCC slabs.

All other design inputs have average NSI values of less than 0.1 in absolute value terms with narrow ranges (see Fig. 1). This means that a 10% decrease in these inputs will cause additional faulting equal to about less than 1% of the design limit of 3.05 mm (0.12 inches). The lower *NSI* values for these inputs indicate that they do not have much influence on faulting predictions in the new JPCP.

Fig. 2 summarizes the *NSI* values for faulting of JPCP over stiff foundation cases. The design inputs for faulting of JPCP over stiff foundation cases have sensitive ranking order close to ones for new JPCP. However, the *NSI* values in JPCP over stiff foundation cases are different than those reported for new JPCP.

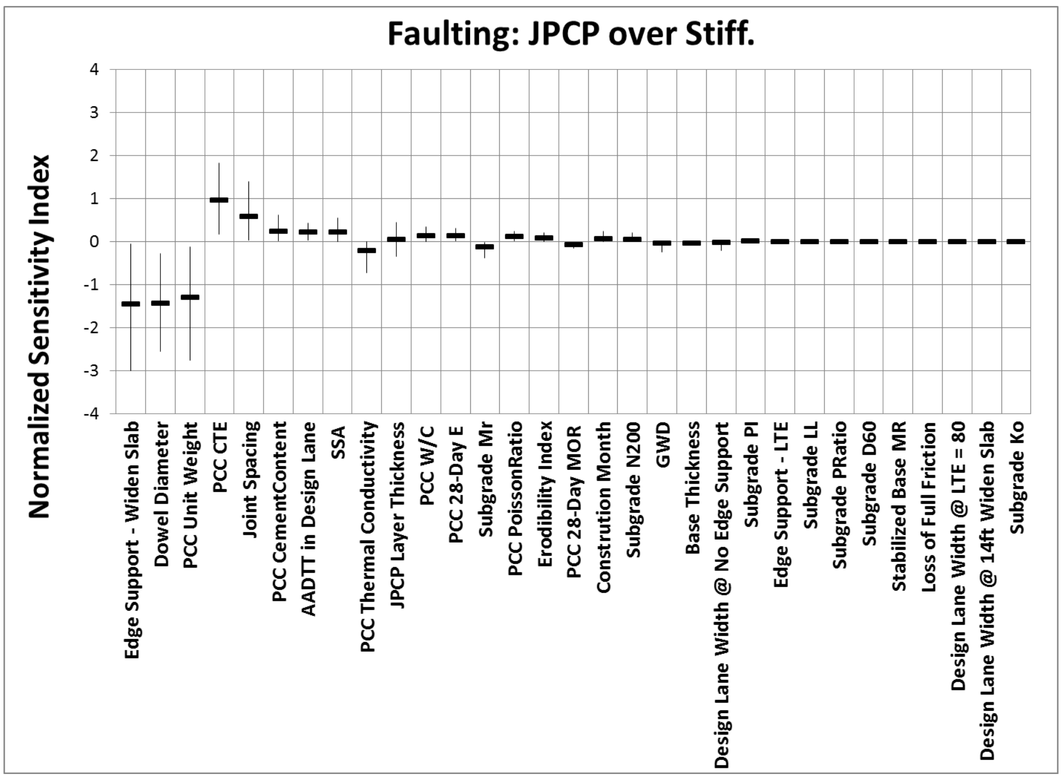

Fig. 2. NSI values for faulting in JPCP over stiff foundation.

Edge support with widened slab and dowel diameter rank as the two most sensitive design inputs for JPCP over stiff foundation, with *NSI* values varying from -0.1 to -3. The next most sensitive design inputs are PCC unit weight with NSI values ranging from -0.1 to -2.8 and PCC CTE with *NSI* values ranging from 0.2 to 2.7. The next set of sensitive inputs includes joint spacing, cement content, AADTT, SSA, PCC thermal conductivity and PCC thickness. Similar to new JPCP cases, the low *NSI* values (less than 0.1 in absolute value terms) for all other design

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inputs in Fig. 2 indicate that they do not have much influence on faulting predictions in the JPCP over stiff foundation cases.

4.3. Transverse cracking performance predictions

The *NSI* values for transverse cracking of new JPCP cases are summarized in Fig. 3. The most sensitive design inputs in decreasing order are PCC 28-day *MOR* with *NSI* values ranging from -9.6 to -16.6, PCC thickness with *NSI* values ranging from -0.6 to -15, joint spacing with *NSI* values ranging from 2.5 to 9.9 and PCC 28-days *E* with *NSI* values ranging from 0.4 to 9.8. Reduced transverse cracking with higher PCC strength and increased PCC thickness agrees with engineering experience. Increased transverse cracking with increasing joint spacing also agrees with engineering experience. Increases in PCC *E* lead to increases in bending stresses that may produce increased transverse cracking. Although in reality PCC *MOR* also increases with increasing PCC *E*, this was not reflected in the OAT analyses that by definition vary only one design input at a time.

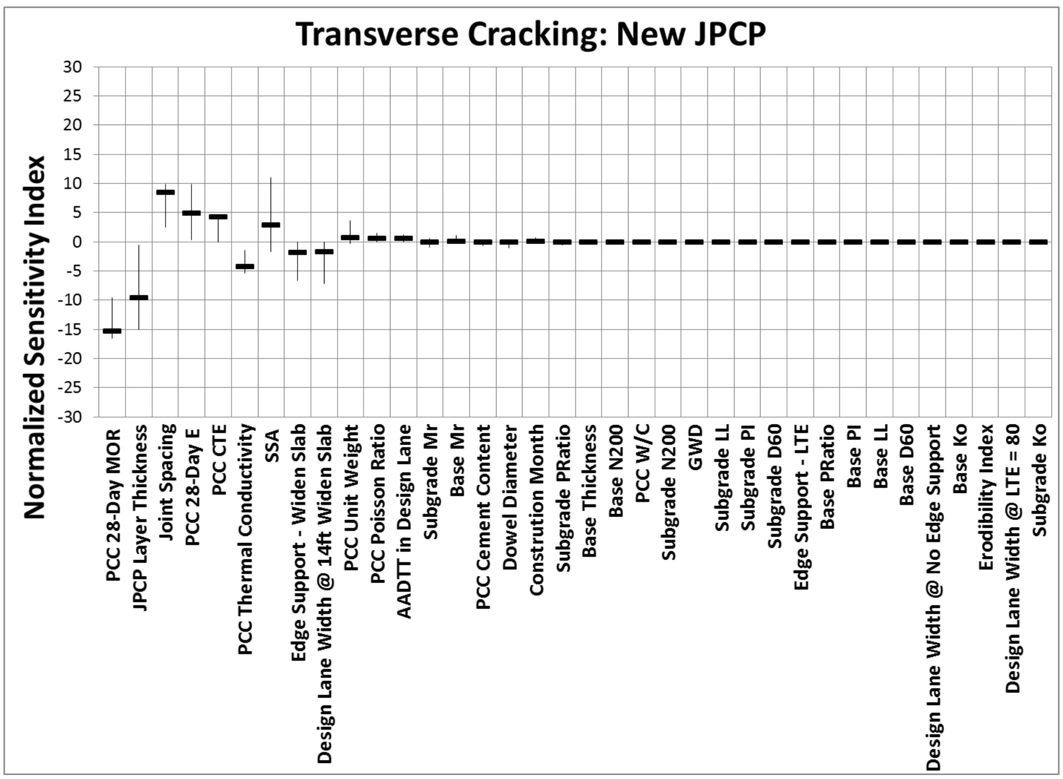

Fig. 3. NSI values for transverse cracking in new JPCP.

The next set of most sensitive design inputs include PCC CTE with *NSI* values varying up to 4.6, thermal conductivity with *NSI* values ranging from -1.4 to -5.3, SSA with *NSI* values varying up to 11, edge support with widened slab with *NSI* values varying down to -6.6, and design lane width under widened slab condition with *NSI* values varying down to -7.2. Higher PCC CTE increases curling stresses resulting in increased transverse cracking. Higher thermal conductivity can decrease curling stress by reducing temperature differences between the top and bottom of PCC slabs, which in turn decreases curling stresses and transverse cracking.

As SSA increases, the pavement surface absorbs more heat from solar radiation, which can make PCC slab surface drier. More drying shrinkage at the top of the slab can result in increased transverse cracking due to warping stress. Wider slabs can greatly reduce tensile bending stresses and transverse cracking by keeping the vehicles axles well away from the free edge and corners of the slabs.

Significant but relatively lower sensitive design inputs include PCC unit weight, PCC Poisson's ratio, and AADTT in design lane. PCC unit weight is an important input in the calculation of critical responses in rigid pavement structural response model employed in the MEPDG. An increase in unit weight can increase curling and warping stresses by restraining slabs from expanding and contracting due to temperature and moisture gradients. PCC Poisson's ratio is a required input to the structural response computation models employed in MEPDG. Although its effect on computed pavement responses is not great, the OAT analyses show that higher PCC Poisson's ratio may increase transverse cracking predictions by increasing the influence of lateral stresses. Increased transverse cracking with increasing AADTT agrees with engineering experience.

The most sensitive design input for the unbound materials is subgrade *Mr*, ranked 13th with average *NSI* values of -0.31. This means that a 10% decrease in subgrade resilient modulus will cause additional transverse carking equal to about 3% of the its design limit. The other unbound material design inputs including (1) granular base layer properties and (2) subgrade material gradation and plasticity properties haves average NSI values of less than 0.1 in absolute value terms with narrow ranges (see Fig. 3). The low *NSI* values for these inputs indicate that they have minor influence on transverse cracking predictions in the new JPCP.

Fig. 4 summarizes the *NSI* values for transverse cracking of JPCP over stiff foundation cases. The design inputs for transverse cracking of JPCP over stiff foundation cases have sensitive ranking order close to the ones for new JPCP. However, the *NSI* values in JPCP over stiff foundation cases are different than those for new JPCP.

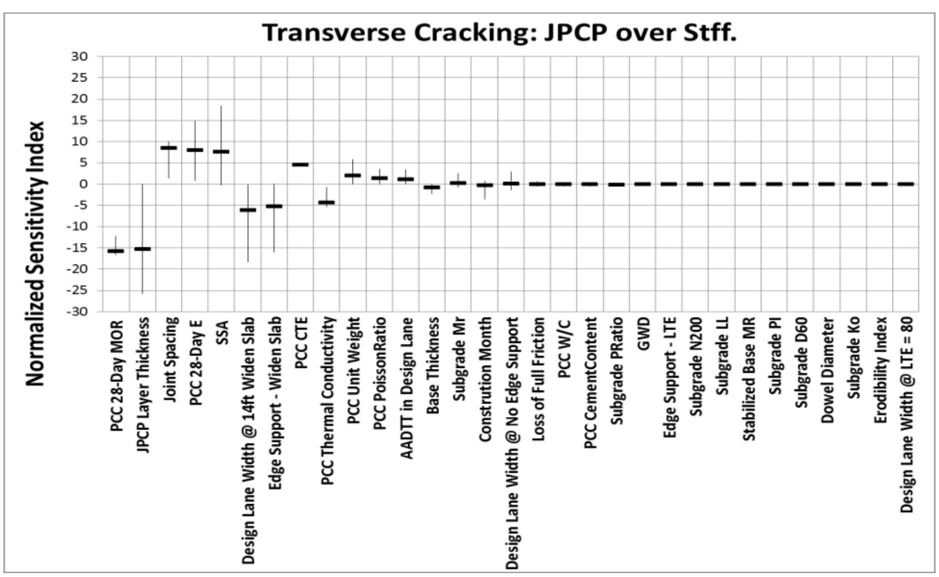

Fig. 4. NSI values for transverse cracking in JPCP over stiff foundation.

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The most sensitive design inputs in decreasing order are PCC 28-day *MOR* with *NSI* values ranging from -12 to -16, PCC thickness with *NSI* values varying up to -26, joint spacing with *NSI* values ranging from 1.4 to 10, PCC 28-days *E* with *NSI* values ranging from 0.9 to 15, SSA with *NSI* values ranging varying down to -26, design lane width under widen slab varying down to -18, and edge support with widened slab with *NSI* values varying down to -16.

The next set of most sensitive design inputs include PCC CTE with *NSI* values of about 4.5 and PCC thermal conductivity with *NSI* values ranges from -0.8 to -5.4, followed PCC unit weight, PCC Poisson's ratio, and AADTT, and base thickness. Similar to new JPCP cases, unbound material design inputs in Fig. 4 have lower *NSI* values indicating lower influence on transverse cracking predictions in the JPCP over stiff foundation cases.

4.4. IRI performance predictions

The *NSI* values for predicted IRI of the new JPCP cases are summarized in Fig. 5. IRI predictions in MEPDG are calculated from regression equations that have as principal inputs the primary distresses (e.g., faulting and transverse cracking) along with a site factor. This means that the highly sensitive design inputs for faulting and /or transverse cracking will also be sensitive design inputs for IRI predictions.

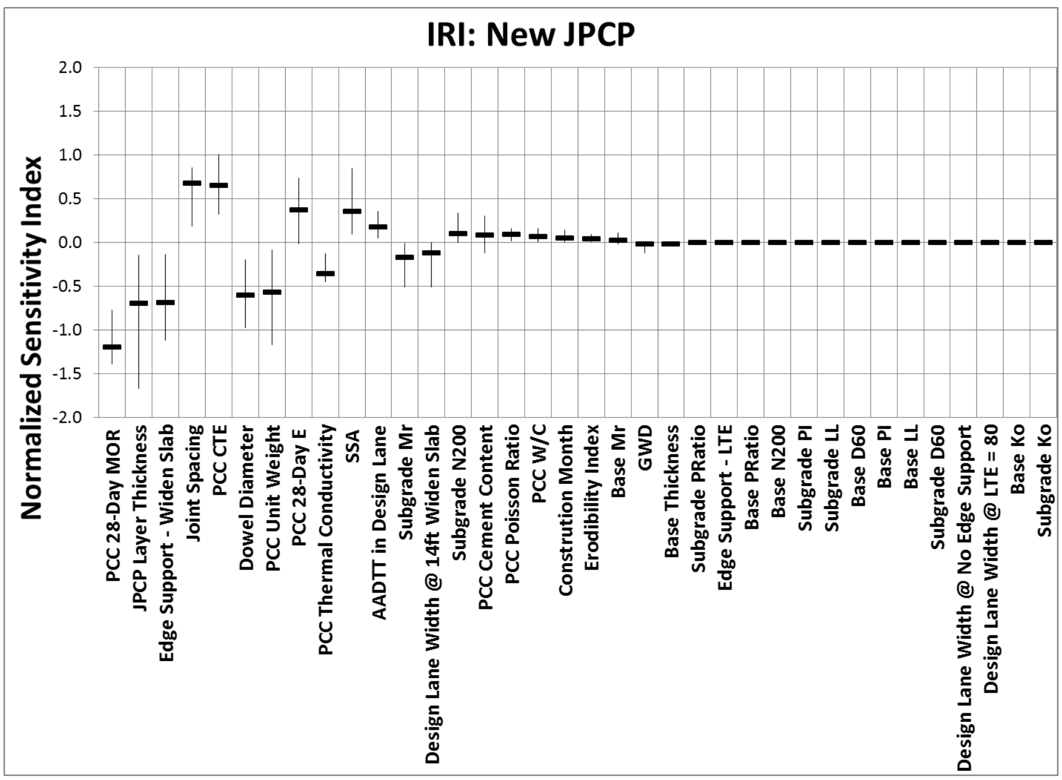

Fig. 5. NSI values for IRI in new JPCP.

The most sensitive design inputs for IRI predictions include PCC 28-day *MOR*, PCC thickness, edge support with widened slab, joint spacing, PCC CTE, dowel diameter, and PCC unit weight. Note that the average *NSI* values of these design inputs are higher than 0.5.

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Among these, the sensitive design inputs for both faulting and transverse cracking predictions are PCC thickness, edge support with widened slab, joint spacing, PCC CTE, and PCC unit weight. Increased PCC thickness in these OAT analyses resulted in a decrease in predicted faulting and predicted transverse cracking. A widened slab can also improve IRI by reducing faulting and transverse cracking. Higher PCC CTE and increased joint spacing increase predicted IRI by increasing both faulting and transverse cracking predictions. Increased PCC unit weight in these OAT analyses resulted in a decrease in predicted faulting and an increase in predicted transverse cracking. The net effect is that increased PCC unit weight causes a decrease in predicted IRI.

Among the sensitive design inputs for predicted IRI, those that are also sensitive design inputs for predicted transverse cracking alone are PCC 28-day *MOR*. The only sensitive design input for predicted faulting is dowel diameter. As stated previously, these design inputs are the most sensitive for individual distress prediction. Thus, it is reasonable that theses design inputs are also sensitive for predicted IRI. A higher PCC 28-day *MOR* can improve IRI by reducing transverse cracking. Increased dowel diameter can also improve IRI by reducing faulting.

The *NSI* values for predicted IRI of the JPCP over stiff foundation cases are summarized in Fig. 6. The most sensitive design inputs for new JPCP cases are also ones for JPCP over stiff foundation cases. In addition to these inputs, the average *NSI* values of PCC 28-day *E* and SSA are higher than 0.5. These design inputs are also highly sensitive for faulting and/or transverse cracking predictions.

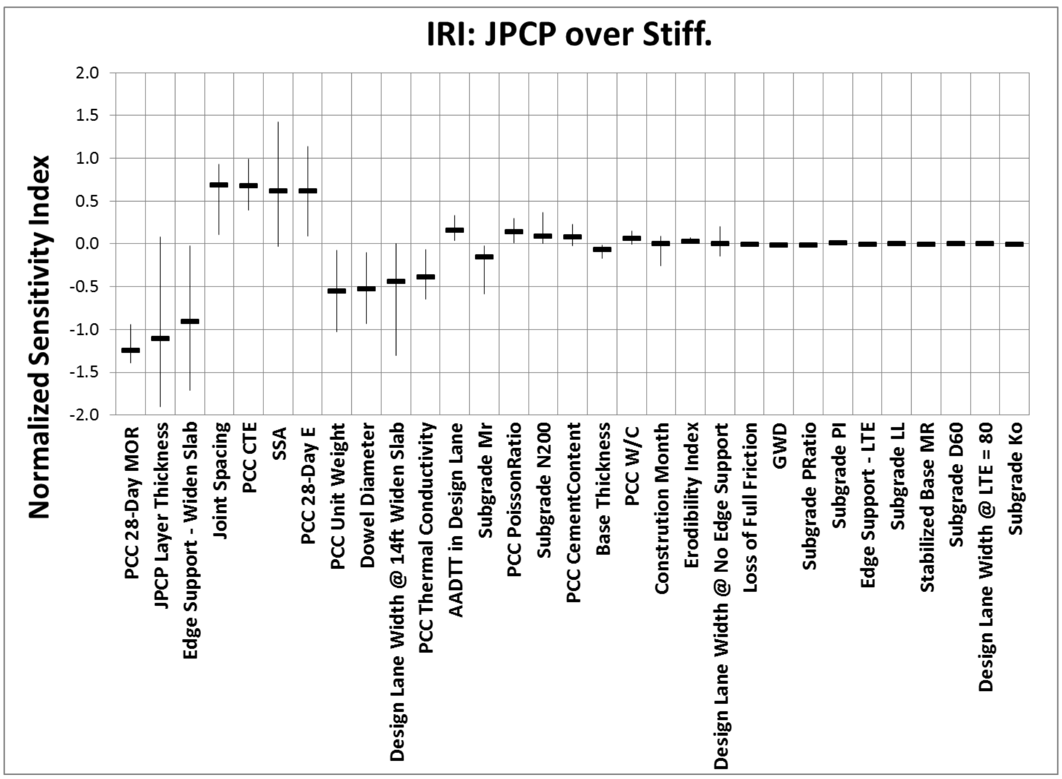

Fig. 6. NSI values for IRI in JPCP over stiff foundation.

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5. Discussion of Sensitivity Results

Table 7 and 8 provide design input sensitivities on three performance predictions in new JPCP and JPCP over stiffness foundation cases, respectively. The maximum absolute *NSI* (|*NSI*|) presented in these tables is the largest *NSI* value (in an absolute value sense) calculated for the design input for any pavement type, base case, or distress. The sensitivity ratings based on the maximum absolute *NSI* are categorized as Hyper Sensitive (HS), NSI > 5; Very Sensitive (VS), 1 < NSI < 5; Sensitive (S), 0.1 < NSI < 1; and Non Sensitive (NS), NSI < 0.1.

Table 9 summarizes the design inputs having maximum absolute *NSI* value of higher than 1.0 for three performance predictions in both new JPCP and JPCP over stiffness foundation cases. An absolute *NSI* value of higher than 1.0 means that 10% change in these inputs will change performance prediction by more than 10% of their design limits. These design inputs can be considered as hyper or very sensitive (HS or VS) inputs.

PCC slab design features and PCC material properties are more sensitive than the other design inputs required in MEPDG/DARWin-ME™. The design inputs sensitive to all three performance predictions are PCC layer thickness, edge support with widened PCC slab, and the curling and warping related inputs (PCC CTE and unit weight). Joint spacing is very sensitive to faulting and transverse cracking predictions. Although the PCC strength (*MOR*) and stiffness (*E*) are not very sensitive to all three performance predictions, the absolute *NSI* values of these inputs to transverse cracking prediction are the highest values among PCC materials properties. Increases in PCC strength results in decreasing transverse cracking predictions while increases in PCC stiffness results in increasing transverse cracking predictions. A 10% increase in PCC strength decreases transverse cracking by more than one-and-half of cracking design limit (15%). A 10% increase in PCC stiffness increases transverse cracking by about as much as cracking design limit.

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Table 7. Design input sensitivities on performance predictions for new JPCP.

Performance Predictions	Faulting		Trans. Crack		IRI	
	Max |NSI|	Sensitivity Category	Max |NSI|	Sensitivity Category	Max |NSI|	Sensitivity Category
AADTT in Design Lane	0.92	S	1.25	VS	0.35	S
Base D60	0.04	NS	0.07	NS	0.01	NS
Base Ko	0.00	NS	0.07	NS	0.00	NS
Base LL	0.00	NS	-0.07	NS	-0.01	NS
Base Mr	0.31	S	1.07	VS	0.11	S
Base N200	-0.04	NS	0.13	S	0.01	NS
Base PI	-0.04	NS	-0.07	NS	-0.01	NS
Base PRatio	0.04	NS	-0.13	S	0.01	NS
Base Thickness	-0.18	S	-0.20	S	-0.07	NS
Construction Month	0.38	S	0.67	S	0.14	S
DLW @ 14ft Widen Slab	0.00	NS	-7.20	HS	-0.51	S
DLW @ LTE = 80	0.00	NS	0.00	NS	0.00	NS
DLW @ No Edge Support	0.00	NS	-0.08	NS	0.00	NS
Dowel Diameter	-2.46	VS	-1.10	VS	-0.98	S
Edge Support - LTE	-0.02	NS	-0.07	NS	-0.01	NS
Edge Support - Widen Slab	-2.90	VS	-6.60	HS	-1.12	VS
Erodibility Index	0.25	S	0.01	NS	0.09	NS
GWD	-0.32	S	-0.11	S	-0.12	S
Joint Spacing	1.59	VS	9.91	HS	0.85	S
JPCP Layer Thickness	-1.73	VS	-15.03	HS	-1.67	VS
PCC 28-Day E	0.29	S	9.87	HS	0.73	S
PCC 28-Day MOR	-0.19	S	-16.55	HS	-1.39	VS
PCC Cement Content	0.83	S	-0.71	S	0.30	S
PCC CTE	1.85	VS	4.63	VS	1.01	VS
PCC PRatio	0.28	S	1.53	VS	0.16	S
PCC Thermal Conductivity	-0.28	S	-5.33	HS	-0.45	S
PCC Unit Weight	-3.38	VS	3.60	VS	-1.17	VS
PCC W/C	0.42	S	-0.30	S	0.16	S
SSA	2.64	VS	10.99	HS	0.84	S
Subgrade D60	0.00	NS	0.13	S	0.01	NS
Subgrade Ko	0.00	NS	0.00	NS	0.00	NS
Subgrade LL	0.04	NS	-0.10	NS	0.02	NS
Subgrade Mr	-0.30	S	-0.86	S	-0.51	S
Subgrade N200	0.13	S	-0.10	NS	0.34	S
Subgrade PI	0.04	NS	-0.10	NS	-0.01	NS
Subgrade PRatio	0.04	NS	-0.60	S	-0.04	NS

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Table 8. Design input sensitivities on performance predictions for JPCP over stiff foundation.

Performance Predictions	**Faulting**		**Trans. Crack**		**IRI**	
	Max |NSI|	**Sensitivity Category**	**Max |NSI|**	**Sensitivity Category**	**Max |NSI|**	**Sensitivity Category**
AADTT in Design Lane	0.44	S	3.40	VS	0.33	S
Base Thickness	-0.08	NS	-2.34	VS	-0.17	S
Construction Month	0.24	S	-3.62	VS	-0.26	S
DLW @ 14ft Widen Slab	0.00	NS	-18.32	HS	-1.30	VS
DLW @ LTE = 80	0.00	NS	0.00	NS	0.00	NS
DLW @ No Edge Support	-0.20	S	2.88	VS	0.20	S
Dowel Diameter	-2.54	VS	-0.02	NS	-0.93	S
Edge Support - LTE	-0.01	NS	-0.18	S	-0.02	NS
Edge Support - Widen Slab	-3.00	VS	-16.00	HS	-1.71	VS
Erodibility Index	0.20	S	0.00	NS	0.07	NS
GWD	-0.24	S	-0.31	S	-0.09	NS
Joint Spacing	1.39	VS	9.98	HS	0.93	S
JPCP Layer Thickness	0.45	S	-25.86	HS	-1.90	VS
Loss of Full Friction	0.00	NS	0.60	S	0.04	NS
PCC 28-Day E	0.31	S	14.82	HS	1.14	VS
PCC 28-Day MOR	-0.15	S	-16.62	HS	-1.39	VS
PCC Cement Content	0.63	S	-0.50	S	0.23	S
PCC CTE	1.82	VS	4.63	VS	1.00	S
PCC Pratio	0.25	S	3.56	VS	0.30	S
PCC Thermal Conductivity	-0.73	S	-5.35	HS	-0.65	S
PCC Unit Weight	-2.75	VS	-5.80	HS	-1.02	VS
PCC W/C	0.35	S	-0.53	S	0.15	S
SSA	0.55	S	18.45	HS	1.42	VS
Stabilized Base MR	-0.01	NS	-0.09	NS	-0.01	NS
Subgrade D60	0.04	NS	0.07	NS	0.01	NS
Subgrade Ko	0.00	NS	-0.03	NS	0.00	NS
Subgrade LL	-0.04	NS	-0.13	S	0.02	NS
Subgrade Mr	-0.38	S	2.53	VS	-0.58	S
Subgrade N200	0.21	S	0.30	S	0.37	S
Subgrade PI	0.13	S	-0.27	S	0.10	NS
Subgrade PRatio	-0.04	NS	-0.50	S	-0.10	NS

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Table 9. Design inputs with maximum |NSI| >1 for JPCPs.

Performance Predictions	**Input Category (Max.|NSI| for new JPCP/ Max.|NSI| for JPCP over stiff foundation)**	
	PCC Properties	**Non PCC Properties**
Faulting	***PCC Unit Weight (-3.38/-2.75)[1]*** ***Edge Support - Widen Slab (-2.90/-3.00)[1]*** Dowel Diameter (-2.46/-2.74) ***PCC CTE (1.85/1.82)[1]*** ***PCC Layer Thickness (-1.73)[1]*** Joint Spacing (1.59/1.39)	
Trans. Crack	PCC 28-Day MOR (-16.6/-16.6) ***PCC Layer Thickness (-15.0/-25.9)[1]*** Joint Spacing (9.9/10.0) PCC 28-Day E (9.9/14.8) Design Lane Width @ 14ft Widen Slab (-7.2/-18.3) ***Edge Support - Widen Slab (-6.6/-16.0)[1]*** PCC Thermal Conductivity (-5.3/-5.4) ***PCC CTE (4.6/4.6)[1]*** ***PCC Unit Weight (3.6/5.8)[1]*** PCC Poisson Ratio (1.5/3.6)	SSA (11.0/18.4) AADTT (1.3/3.4)
IRI	***PCC Layer Thickness (-1.67/-1.9)[1]*** PCC 28-Day MOR (-1.39/-1.39) ***PCC Unit Weight (-1.17/-1.02)[1]*** ***Edge Support - Widen Slab (-1.12/-1.71)[1]*** ***PCC CTE (1.01/1.0)[1]***	

[1] The design inputs sensitive to all three performance predictions

6. Summary and Conclusions

Jointed Plain Concrete Pavement (JPCP) sections representing new construction and rehabilitation conditions were designed for three traffic levels in five climate zones to qualitatively and quantitatively evaluate the sensitivity of predicted distresses from the MEPDG. Sensitivity is characterized by a design limit normalized sensitivity index *NSI*, which can be interpreted as the percentage change in predicted distress relative to the design limit caused by a given percentage change in the design input. The analyses found that, for JPCP types and distresses, the sensitivities of the design inputs for the JPCP surface layers were consistently the highest. These design inputs include the PCC layer thickness, edge support with widened PCC slab, joint spacing, PCC strength and stiffness properties, and the curling and warping related properties. This finding suggests that more caution is required to select PCC slab design features and PCC material properties in JPCP design using MEPDG and DARWin-ME™. In unbound layer properties, the subgrade stiffness property (*Mr*) is more sensitive than the other unbound material design inputs but is not highest ranked in all design inputs. This suggests that the level of structural contribution of unbound layer properties in the MEPDG JPCP performance modeling may need further examination.

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